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CHARACTERIZING THE SMALL SCALE STRUCTURE IN CLUSTERS OF GALAXIES

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1 Introduction

We have been investigating different techniques for determining the presence of small-scale structure in clusters of galaxies. A first paper has been accepted for publication in the Astrophysical Journal Letters and a second is in preparation. We discuss the status and results from each of these below.

2 A New Wavelet Technique Applied to the ROSAT Image of the Coma Cluster

The first paper, "Another Collision for the Coma Cluster" by Vikhlinin, Forman, and Jones describes a wavelet transform analysis of the ROSAT PSPC images of the Coma cluster. The technique we applied to the ROSAT PSPC "cleaned" images employs a set of *à trous* wavelet transforms with some new approaches in the iteration scheme.

2.1 Wavelet Technique

The *à trous* wavelet transform of scale a can be (very roughly) characterized as the convolution of an image with the function equal to the difference between two Gaussians, the first positive one with $\sigma = a$, and the second negative one with $\sigma = 2a$. The basic idea of the wavelet-based image filtering is to perform the set of wavelet transforms with scales $a, 2a, 4a...$, retain only significant wavelet coefficients at each scale (thus filtering out the noise), and perform the image reconstruction from the wavelet planes. For the *à trous* wavelet transform, the reconstruction is performed by simple summation of all wavelet planes. At each scale we retain the wavelet coefficients which exceed some critical amplitude which corresponds to the given number of standard deviations (3σ in our application). To assure the most complete separation of image features in terms of their scale, we apply the following iterative procedure. We start from the smallest scale, $a = 30''$, which roughly corresponds to the FWHM of the ROSAT PSPC PSF. We calculate the wavelet transform on this first scale only, find significant features, and subtract them from the original image (recall that the back-transformation for the *à trous* wavelet transform is simply the summation of the wavelet planes). The next iteration is applied to the residual and this process is repeated until no new significant features are found at this scale. We then start the process with the scale $2a$ and so on. The subtraction of the features detected at smaller scales before applying the wavelet transform at larger scales results in a sufficient enhancement of the basic property of the wavelet transform analysis — its ability to separate image features in terms of their characteristic scale. In particular, we are able to isolate even extremely bright point sources primarily at the two smaller scales (i.e. $\leq 60''$), whereas without subtraction, they appear at all scales and often saturate nearby and relatively faint extended structures.

The process described above provides a separation of the original image into a set of images containing only features of scale a, $2a$, ... significant at least at the 3σ level, which can be either summed together to produce an adaptively smoothed image or viewed individually (or in any desired combination) to examine the significant structures at desired scales.

2.2 Coma Cluster Results

On small scales, $\leq 1'$, the wavelet analysis shows substructure dominated by two extended sources surrounding the two brightest cluster galaxies NGC 4874 and NGC 4889. On slightly larger scales, $\sim 2'$, the wavelet analysis reveals a filament of X-ray emission originating near the cluster center, curving to the south and east for $\sim 25'$ in the direction of the galaxy NGC 4911, and ending near the galaxy NGC 4921. These results extend earlier ROSAT observations and further indicate the complex nature of the cluster core. We consider two possible explanations for the production of the filamentary feature as arising from interactions of the main cluster with a merging group. The feature could arise from either ram pressure stripped gas or a dark matter perturbation of tidally stripped material.

The wavelet analysis of the ROSAT PSPC X-ray images of the Coma cluster demonstrates the existence of a new feature possibly associated with dynamical activity in the cluster core. We can estimate the physical parameters associated with this filament of emission assuming it arises from hot gas. Let us assume that we are viewing the filament in the plane of the sky and it is a uniform cylinder of radius 100 kpc and length 1 Mpc. The observed 10% surface brightness enhancement implies that the density of the filament must exceed the cluster gas density at least by about 5%. Since the relative brightness of the filament does not change much along it axis, the gas density in the filament should vary as a function of radius from the cluster center. Assuming that the gas is not particularly cool ($T >$ a few keV), we derive a total average gas density in the volume defined by the filament of approximately 10^{-3} cm^{-3} with a range from about 2.5×10^{-4} to 2.5×10^{-3} cm^{-3}. We emphasize that this is the total gas density, not just the gas density perturbation required to generate the observed surface density enhancement. This density translates into a gas mass of 5×10^{11} solar masses.

We have shown that the filament could arise from 1) ram pressure stripped gas from a group passing through Coma, especially if magnetic fields significantly reduce the conduction efficiency and lengthen the evaporation time or 2) tidally stripped dark matter from a merging group could produce a perturbation that would give rise to the observed structure.

3 Search for Filamentary Features in Cooling Flow Clusters

We are analyzing three clusters — 2A0335, Sersic 159, and A426 to assess the statistical significance of small scale structures in the X-ray gas. We used two independent approaches to analyze the data. In the first, we compared the number of counts in apertures surrounding areas containing potential filaments with that expected from a smooth β model. In the second, we have performed a wavelet analysis of the data at scales from 2 arcsec to 25 arcsec.

From our analysis and modeling we find that though there may be some structure in both Sersic 159 and 2A0335, it is generally not at very high levels of significance and is not very complex in morphology as was suggested in previous papers. The data differs only marginally from simulations of smooth emission but differs qualitatively from a cluster with recognized structure.

This analysis is nearly complete, but a refined analysis using non-azimuthally symmetric wavelets is planned. This is especially important to understand the significance of long narrow filaments that may be characteristic of cooling flow clusters.